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PHASE I FINAL REPORT

VOLUME IA - PART 1
EXECUTIVE SUMMARY

SYSTEM TECHNOLOGY ANALYSIS OF AEROASSISTED ORBITAL TRANSFER VEHICLES: MODERATE LIFT/DRAG (0.75-1.5)

AUGUST 1985

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GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER , ALABAMA 35812

BY

RE-ENTRY SYSTEMS OPERATIONS
3198 Chestnut St., Philadelphia, PA 19101

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FORWARD

This final report of the "System Technology Analysis of Aeroassisted Orbital Transfer Vehicles: Moderate Lift/Drag (0.75-1.5)" was prepared by the General Electric Company, Space Systems Division for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center (MSFC) in accordance with Contract NAS8-35096. The General Electric Company, Space Systems Division was supported by the Grumman Aerospace Corporation as a subcontractor during the conduct of this study. This study was conducted under the direction of the NASA Study Manager, Mr. Robert E. Austin, during the period from October 1982 through June 1985.

The first phase of this program focused on a ground based AOTV and was completed in September 1983. The second phase was directed towards a space based AOTV and the cryofueled propulsion subsystem-configuration interactions and was completed in March of 1985. The second phase was jointly sponsored by NASA-MSFC and the NASA Lewis Research Center (LeRC). Dr. Larry Cooper was the LeRC study manager.

This final report is organized into the following three documents:

Volume IA	Executive Summary - Parts I & II
Volume IB	Study Results - Parts I & II
Volume II	Supporting Research and Technology Report
Volume III	Cost and Work Breakdown Structure/ Dictionary

Part I of these volumes covers Phase 1 results, while Part II covers Phase 2 results.

The following personnel were major contributors to this study in the areas shown.

Study Manager and Principle Investigator	D.E. Florence (215-823-3129)
Study Manager for Grumman Subcontract	G. Fischer (516-575-2361)
Concept/Configuration Design	R. Hassett G. Fischer K. Sneddon
Propulsion Subsystem	G. Fischer K. Sneddon
Man Rating	G. Fischer
Crew Capsule	G. Fischer
Astrodynamics/Flight Mechanics	W. Letts R. Klund
Aerodynamics	J. Berman J. Gardner C. Harris
Aerothermodynamics	R. Brewer T. LaMonica L. Arrington D. Nestler
Thermal Protection Materials	Dr. R. Tanzilli
Cost Analysis	G. Fischer

VOLUME IA - PART I

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EXECUTIVE SUMMARY - PART I

1.0 INTRODUCTION

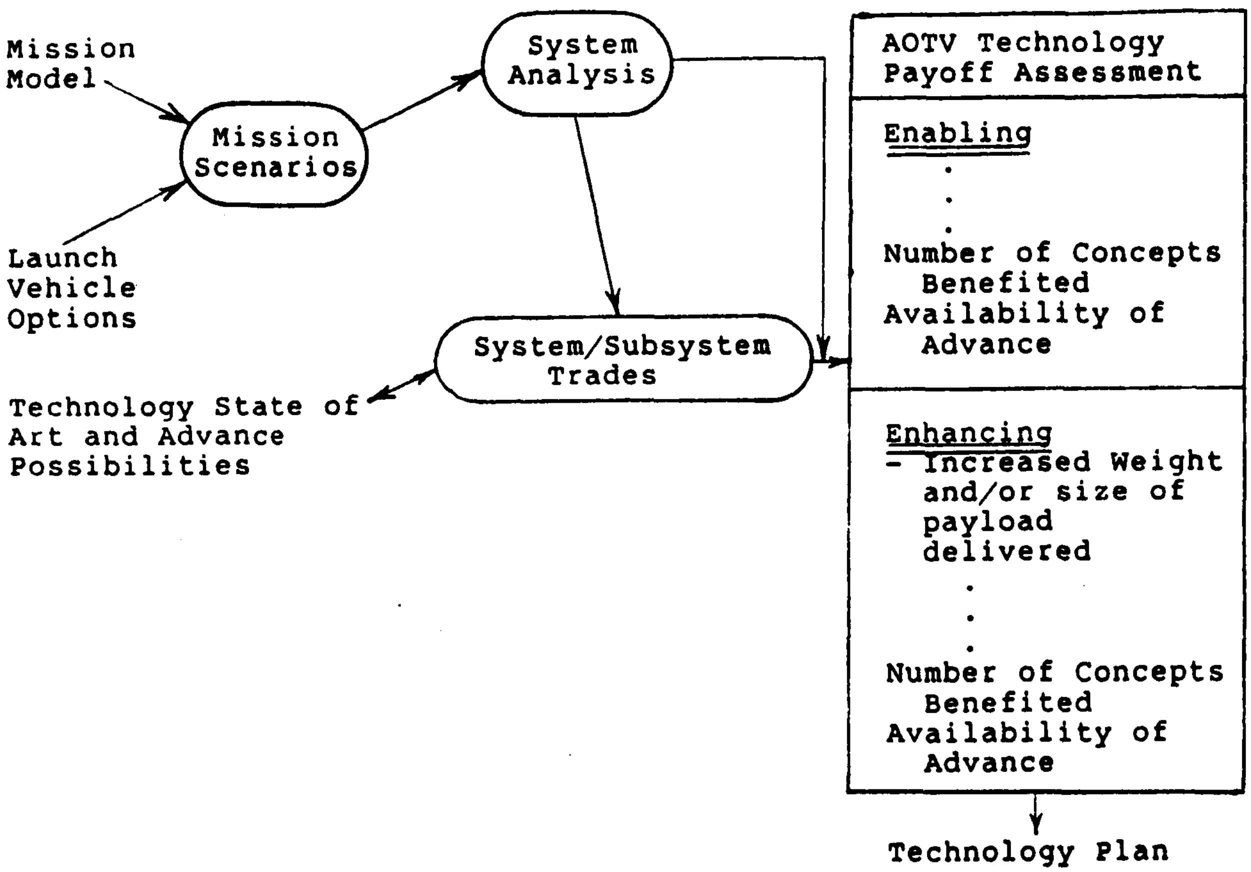
Significant performance benefits can be realized via aerodynamic braking and/or aerodynamic maneuvering on return from higher altitude orbits to low earth orbit (LEO) (1-6). This approach substantially reduces the mission propellant requirements by using aerodynamic drag to brake the vehicle to near circular velocity and aerodynamic lift to null out accumulated errors as well as change the orbital inclination to that required for rendezous with the Space Shuttle Orbiter or Space Station. Previous studies (3,4), have considered only missions from LEO to Geosynchronous orbit (GEO) and return. In this study, missions were also defined to higher inclination orbits, where an aeromaneuvering vehicle was expected to become more attractive due to its ability to provide aerodynamic orbital plane change.

A study has been completed where broad concept evaluations were performed and the technology requirements and sensitivities for ground based aeroassisted OTV's over a range of vehicle hypersonic L/D from 0.75 to 1.5 were systematically identified and assessed.

Part I of this volume contains a narrative summary of the significant achievements and activities of Phase I (Ground based AOTVs) of this study "SYSTEM TECHNOLOGY ANALYSIS OF AEROASSISTED ORBITAL TRANSFER VEHICLES: MODERATE LIFT/DRAG". More detailed coverage of the study results are included in Volume IB, Volume II, and Volume III of this Phase I final report: Study Results, Supporting Research and Technology Report, Cost and Work Breakdown Structure Dictionary.

The major tasks of this study are outlined in Figure 1-1 and include four major areas: System Analyses, System/Subsystem Trades, Technology Payoff Assessment and Plan, and Cost Analysis.

Figure 1-1 Phase I Study Task for System Technology Analysis of Mid L/D AOTV



2.0 SUMMARY OF STUDY FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

The major first order findings and conclusions of this study include the following:

- o Substantial performance improvements and hence cost benefit can be obtained by developing enhancing technologies such as 1) low thrust (2000 to 3000 lbs) advanced expander LOX-hydrogen engines with specific impulse of 480 to 490 sec or 2) reducing the external thermal protection system weight by reducing the coating weight and increasing the maximum allowable bond/structure temperature, or 3) reducing the structural shell weight by improving the quality of the design allowable data, or use of advanced structural materials.

- o Use of mid L/D AOTV provides significant aerodynamic plane change capability (20° for return from GEO with L/D = 1.5) and control authority over trajectory dispersions and off nominal atmospheres.

- o A single STS flight manned mission to GEO with delivery of a one ton payload is possible with the 65 KSTS, mid L/D AOTV, an advanced cryofueled engine and lightweigh ASE (3000 lbs).

- o Delivery of very long payloads (45 ft) is possible by use of very short AOTV's with drop tank.

- o Ground based AOTVs can reduce average Earth to GEO transport costs to $8000/lb for multiple satellite launches.

- o Small vehicles which are used in two stage delivery systems have very different technology cost benefits than larger single stage vehicles.

- o Within any staging class of ground based vehicles, performance sensitivites and technology cost benefits are independent of L/D within the mid L/D range (.75 to 1.5).

- o All mid L/D AOTV enabling technology is ready today.

2.1 Overview of Major Results

Examples of several configuration classes were evaluated. These included both single and multiple stage vehicles; unmanned delivery and manned vehicles. Examples of these configuration, which employ some growth technology are illustrated in Figures 2.1-1, 2 and 3. It appears that the delivered payloads are maximum when the AOTVs are used in a 2 stage mode: perigee impulse is delivered by the AOTV and apogee impulse is delivered by the satellites own station keeping propulsion system (with enlarged tankage for the substantial apogee burn). By launching multiple satellites on the same AOTV flight, earth to GEO delivery costs can average around $8000/lb.

2.1.1 General Mission Model

The generalized mission model addressed is summarized in Figure 2.1-4. The initial ground based AOTV's will be deployed from a 150 nmi circular orbit, launched from ETR at an orbital inclination of 28.5°. The space based AOTV's will be in a 220 nmi circular orbit at 28.5° inclination. Launch vehicles considered include the standard STS, an improved STS, the aft cargo compartment (ACC) and the shuttle derived cargo vehicle.

Operating scenarios were established for the several reference missions and ΔV budgets determined for use in the performance computations, Figures 2.1-5, 6 and 7.

GEO delivery was examined in two modes. In a single stage mode (Figure 2.1-5A), an AOTV delivers the satellites to their final destination at GEO and then returns to LEO. Three major propellant burns are required. In a two stage mode ("perigee kick", Figure 2.1-5B, the AOTV delivers the satellites to an elliptical GEO transfer orbit at 28° inclination. The satellites' own on-board propulsion systems (the GEO station keeping systems, with enlarged propellant tankage) perform the GEO insertion burn (event 4, Figure 2.1-5B) while the AOTV coasts toward return to LEO. Only two small propellant consuming burns (events 6 and 8) are required of the AOTV after payload separation. Effective use of aeromaneuvering orbital plane change during return from Molniya, Figure 2.1-7, is not possible due to the large ΔV required for apsis rotation when leaving the Molniya orbit in order to place the in-atmosphere flight segment near the nodal crossing. Instead it is recommended that the mid L/D AOTV be flown in the braking mode only with aeromaneuvering used for altitude control thus offering a substantial propellant reduction when compared with an all propulsive reusable OTV.

Initial payload capability has been evaluated for a baseline of delivery to GEO, six hour polar, and Molniya (12 hours x 63.4° orbits with return and recovery of the AOTV at LEO. Evolutionary payload requirements that have been assessed include a GEO servicing mission (6K up and 2K return) and a manned GEO mission (14K roundtrip). In addition, the capability to return from 5X GEO was evaluated.

At the current time there are no plans to retrieve or

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Figure 2.1-1 An Internal Tanked AOTV GEO Delivery Vehicle

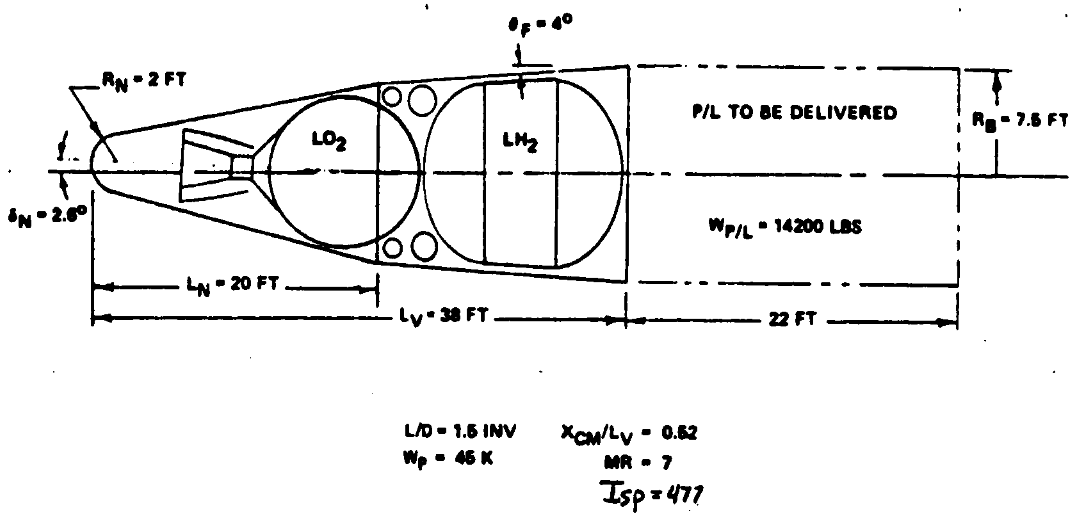
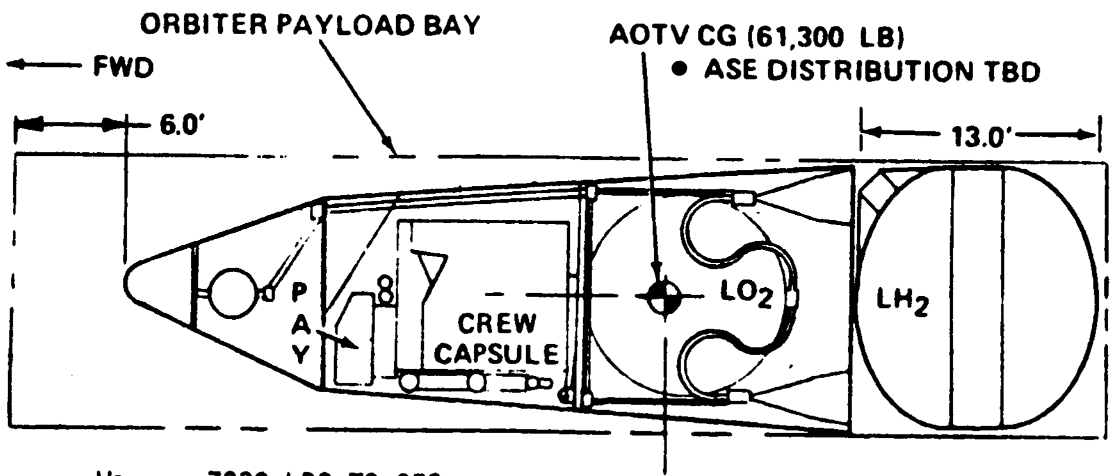
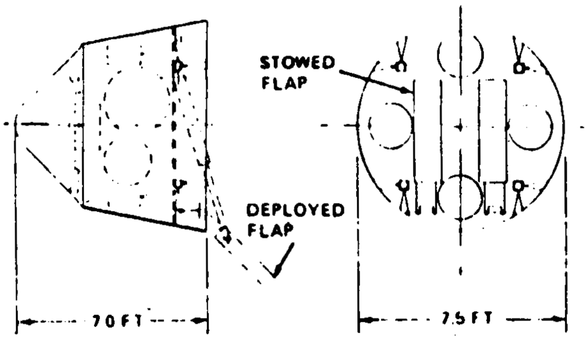


Figure 2.1-2 Manned AOTV "H1" Launch Configuration



$W_{P/L}$ = 7930 LBS TO GEO
5830 LBS RETURN
FOR I_{SP} = 479

Figure 2.1-3 Perigee Kick AOTV-OH-3



OH 3

- FOUR ADVANCED EXPANDER ENGINES
  - ϵ = 400 1
  - I_{SP} = 475 SEC
- TOTAL THRUST - 12,000
- EFFICIENT FOR OFFSET C.G
- POSSIBLE ENGINE OUT CAPABILITY
- 4000 LB DRY WEIGHT
- PAYLOAD DELIVERY TO GEO TRANSFER ORBIT WITH 11,930 LB OF PROP: W_{PAY} - 11,400 LB

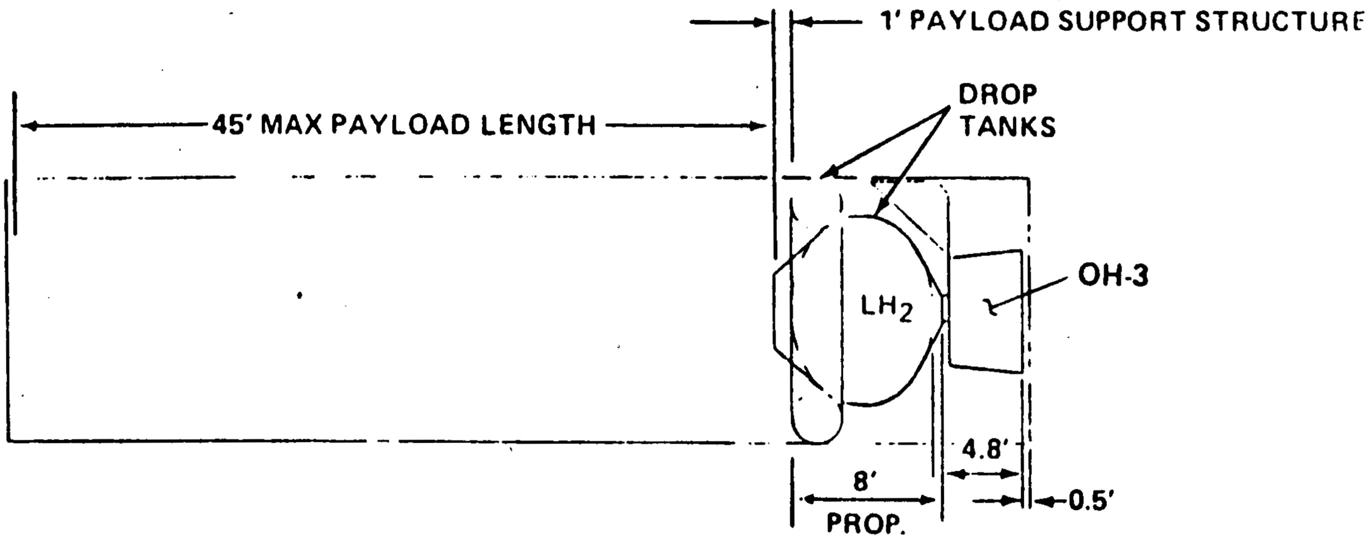


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Figure 2.1-4 AOTV General Mission Model Definition

LEO - LOW EARTH INITIAL PARKING ORBIT

- GROUND BASED 150 NM CIRCULAR, $i = 28.5°$
- SPACE BASED 220 NM CIRCULAR, $i = 28.5°$

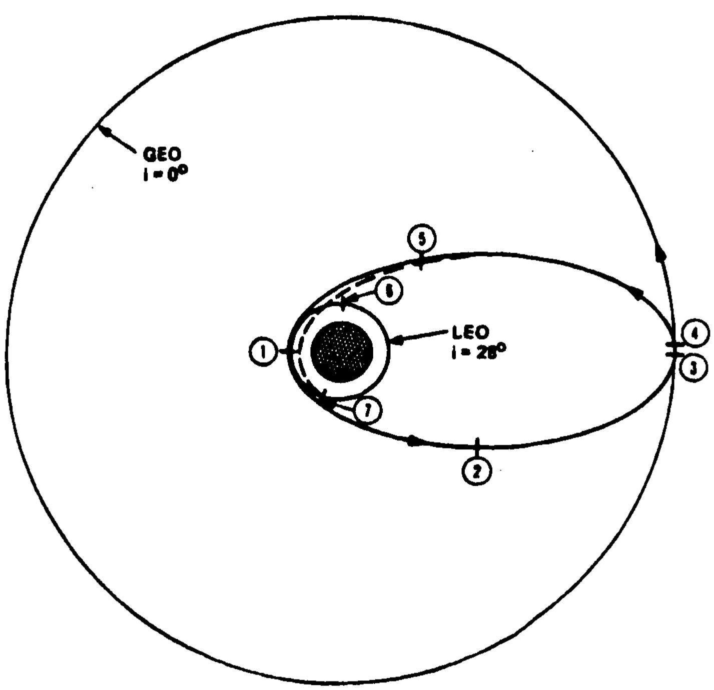
HEO - HIGHER EARTH ORBIT DESTINATIONS

BASELINE {
- GEO - GEOSYNCHRONOUS EQUATORIAL ORBIT, $i = 0°$
- MOLNIYA - 12 HR PERIOD, $i = 63.4°$, $h_a = 21500$ NM, $h_p = 400$ NM

- SIX HOUR POLAR - ETR LAUNCH - 5600 NM CIRCULAR
- 5X GEO

Figure 2.1-5 Operating Scenario for AOTV-GEO Missions

A. Single Stage Transport

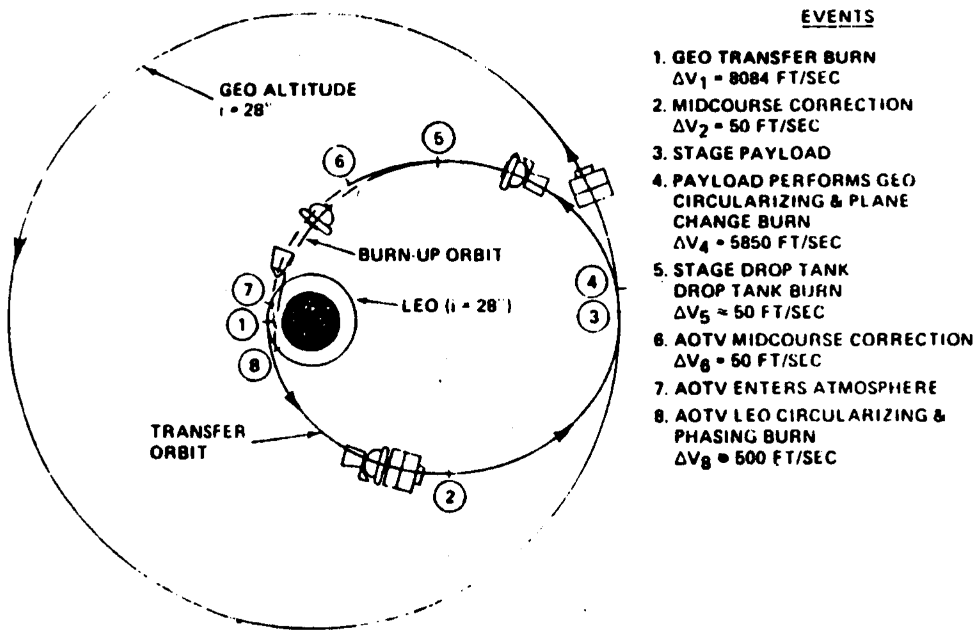


EVENTS

1. GEO TRANSFER BURN
$\Delta V_1 = 8090$ FT/SEC
2. MIDCOURSE CORRECTION
$\Delta V_2 = 50$
3. CIRCULARIZATION AND INCLINATION CHANGE AT GEO
$\Delta V_3 = 6000$
4. TRANSFER TO hp = 80 NMi
$\Delta V_4 = 5414$ FOR L/D = 1.5
Δi AERO = 13°
5. MIDCOURSE CORRECTION
$\Delta V_5 = 50$
6. AOTV ENTERS ATMOSPHERE
7. LEO CIRCULARIZING AND PHASING BURNS
$\Delta V_7 = 450$

Figure 2.1-5 Operating Scenario for AOTV-GEO Missions

B. Two Stage Transport



- AOTV Supplies perigee impulse
- Satellite (payload) supplies apogee impulse

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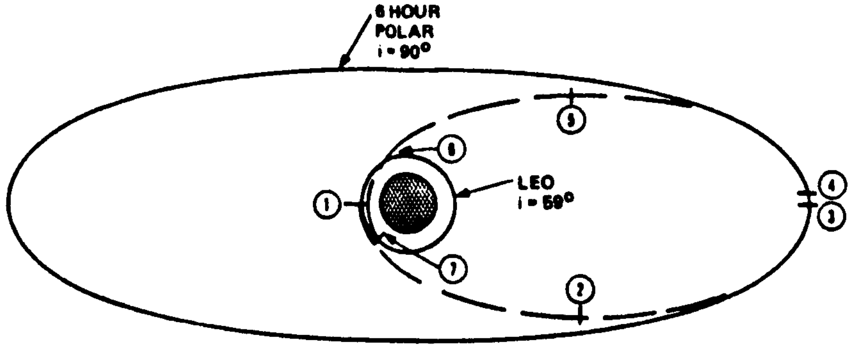
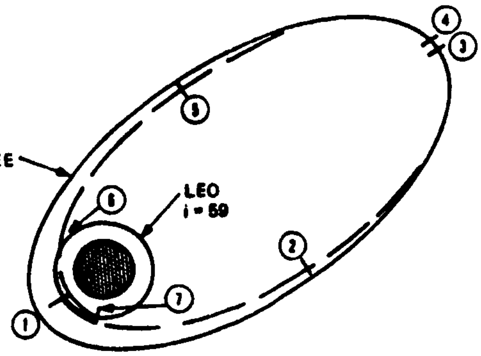
Figure 2.1-6 Operating Scenario for Polar Missions



EVENTS

1. TRANSFER BURN
   ΔV_1 = 5000 FT/SEC
2. MIDCOURSE CORRECTION
   ΔV_2 = 50
3. PLANE CHANGE AND CIRCULARIZATION AT 6 HR POLAR
   ΔV_3 = 7800
4. TRANSFER TO hp = 150 N. MI
   ΔV_4 = 5250 FOR L/D = 1.5
   Δi AERO = 15°
5. TRANSFER hp = 60 N. MI
   ΔV_5 = 110
6. AOTV ENTERS ATMOSPHERE
7. LEO CIRCULARIZATION AND PHASING BURNS
   ΔV_7 = 450

Figure 2.1-7 Operating Scenario for Molniya Missions



- MAXIMUM AERO PLANE CHANGE OBTAINED WHEN IN ATMOSPHERE FLIGHT IS AT NODAL CROSSING
- ΔV PENALTY TO ACCOMPLISH (APSIS ROTATION) IS PROHIBITIVE
- RECOMMEND LIFT VECTOR USED FOR FLIGHT CONTROL ONLY

EVENTS

1. TRANSFER BURN
   ΔV_1 = 8330 FT/SEC
2. MIDCOURSE CORRECTION
   ΔV_2 = 50 FT/SEC
3. PLANE CHANGE AND MOLNIYA INSERTION
   ΔV_3 = 1170
4. TRANSFER TO hp = 60 N MI
   WITH 35° APSIS ROTATION
   AND 3.4° Δi
   ΔV_4 = 8500
   OR
   WITH 5° APSIS ROTATION
   AND 3.4° Δi
   ΔV_4 = 1700
5. MID COURSE CORRECTION
   ΔV_5 = 50
6. AOTV ENTERS ATMOSPHERE
7. LEO CIRCULARIZATION AND PHASING BURNS
   ΔV_7 = 450

carry payloads on the return leg of the mission. However, by use of a plane changing propulsive burn at initiation of the return leg and another propulsive burn at LEO for circularization (no aeroassist), payloads could be returned without being enclosed in a TPS covered shroud.

Present expectations are for a manned space station to be operational several years before the first new reuseable OTV becomes operational. With a significant manned presence in space, manned OTV missions may be desired immediately, or shortly after, a new reuseable OTV becomes operational. Consequently, the initial AOTV may be a manned (or man related) vehicle.

2.1.2 Aeromechanic Performance

Previous studies (3,4) have considered only missions from LEO to GEO and return. In this study, missions were defined to higher inclination orbits, where an aero- maneuvering vehicle was expected to become more attractive due to its ability to provide orbital plane change without consuming much propellant.

Performance studies have been conducted for return of mid L/D vehicles from GEO, 5 x GEO, and 6-hour polar circular orbits. Steering laws have been employed that include constant deceleration cruise at the overshoot and undershoot bounds, and constant bank angle cruise. Aerodynamic orbital plane change obtained is summarized in Figure 2.1-8, where it is shown that plane change capability increases with hypersonic L/D and entry velocity (maximum for the 5 x GEO return) for a specific steering law. A 90^o bank angle provides the maximum plane change.

Use of the various steering laws results in different minimum altitudes and thus different maximum heating rates, Figures 2.1-9, 2.1-10 and 2.1-11. It can be noted that maximum heat transfer rate increases with vehicle ballistic coefficient, W/CDA, with increasing entry velocity (5 x GEO results in maximum entry velocity) and with decreasing minimum flight altitudes (constant 90^o bank angle results in minimum flight altitudes).

2.1.3 <u>Payload Delivery Sensitivites</u>

Flight performance and payload delivery sensitivities across the mid L/D range for a single stage AOTV are summarized in Figure 2.1-12. The incremental increase in payload delivery capability, given a reduction in vehicle dry weight, $\Delta WP/L/\Delta WT_{dry}$, or an increase in engine specific impulse, $\Delta W\ P/L/\Delta Isp$, or an incremental increase in vehicle L/D, $\Delta W\ P/L/\Delta L/D$, is illustrated for vehicles at both ends of the mid L/D range. The incremental loss of payload delivery capability is illustrated for each degree of plane change generated propulsively in the initial mission orbit. Note the large

Figure 2.1-8 Effect of Mission, Steering Law, and Lift to Drag Ratio on Aerodynamic Orbital Plane Change

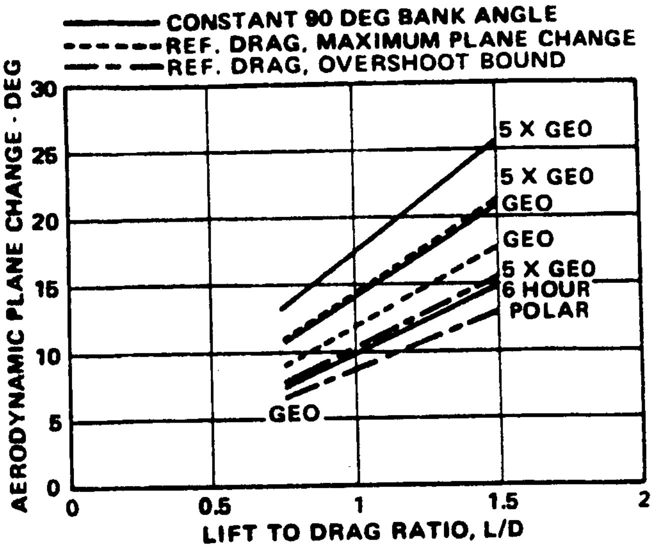


Figure 2.1-9 Effect of Ballistic Coefficient and Steering Law on Peak Convective Stagnation Point Heat Transfer Rate

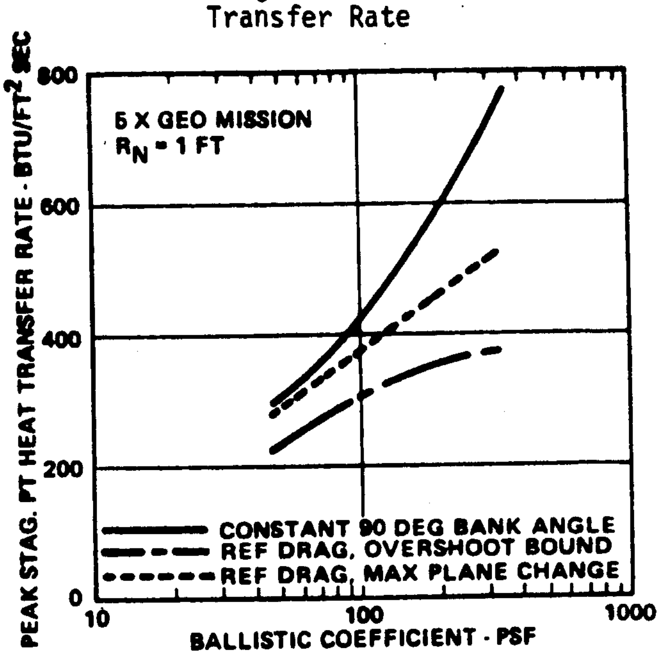


Figure 2.1-10 Effect of Ballistic Coefficient and Steering Law on Minimum Flight Altitude

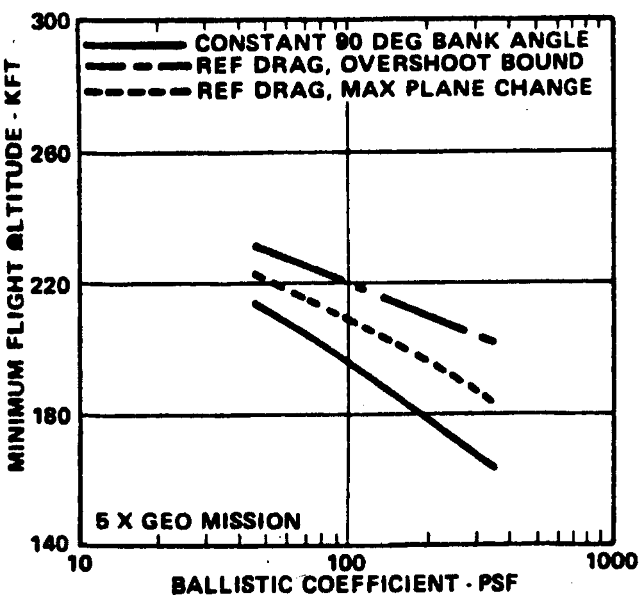


Figure 2.1-11 Effect of Ballistic Coefficient and Mission on Peak Convective Stagnation Point Heat Transfer Rate

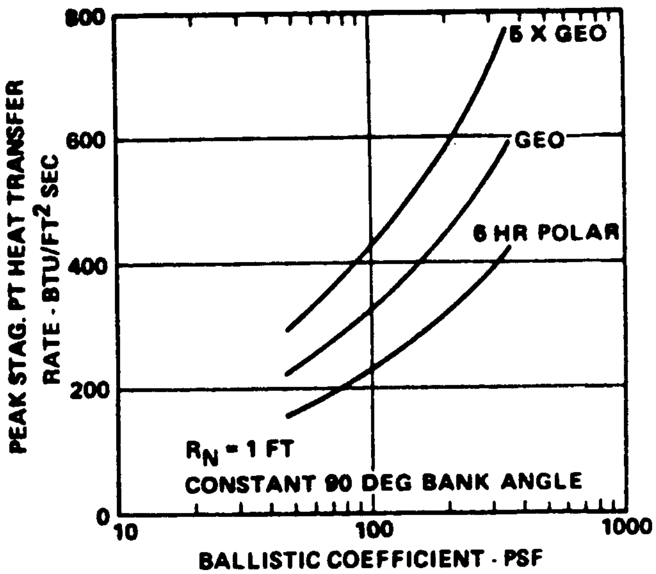


Figure 2.1-12 Summary of Payload Delivery Sensitivities for An Internal Tanked AOTV-65K STS

PARAMETER		MISSION	P/L SENSITIVITIES	
			L/D = 0.75	1.5
AOTV DRY WEIGHT	$\Delta W_{P/L} / \Delta WT_{DRY}$ (LB/LB)	GEO DELY	-1.65	-1.65
		6 HR POLAR	-1.7	-1.5
ENGINE I_{SP}	$\Delta W_{P/L} / \Delta I_{SP}$ (LB/SEC)	GEO DELY	64	64
		6 HR POLAR	58	50
LIFT-DRAG RATIO	$\Delta W_{P/L} / \Delta L/D$ (LB)	GEO DELY	430	430
		6 HR POLAR	2000	1700
		GEO MANNED RT	800	800
PROPULSIVE PLANE CHANGE AT MISSION ALTITUDE	$\Delta W_{P/L} / \Delta i_{PROP}$ (LB/o)	GEO DELY	-34	-34
		6 HR POLAR	-183	-183

Figure 2.1-13 Technology Advancement Potential

AOTV Subsystem Element	Expected Improvement
Structure (shell, frames, supports and flaps - Improved Design Allowables - New Materials	10 to 30% weight reduction
Thermal Protection System - Reduced Coating Weight - Non-catalytic Coatings - Increased Bond/Structure and maximum surface temperatures	Up to 56% weight reduction
Transpiration Cooled Nose	7^{o} plane change increase for 5X GEO return
Avionics - Degree of Autonomy/Redundancy	50 to 70% weight reduction
Electrical Power Supply - New Materials	20 to 38% weight reduction
New Cryofueled Engine - High Chamber Pressure - Mixture Ratio 6-7	Isp up to 480 seconds

Figure 2.1-14 Effect of Technology Advances on Customer Cost Benefit

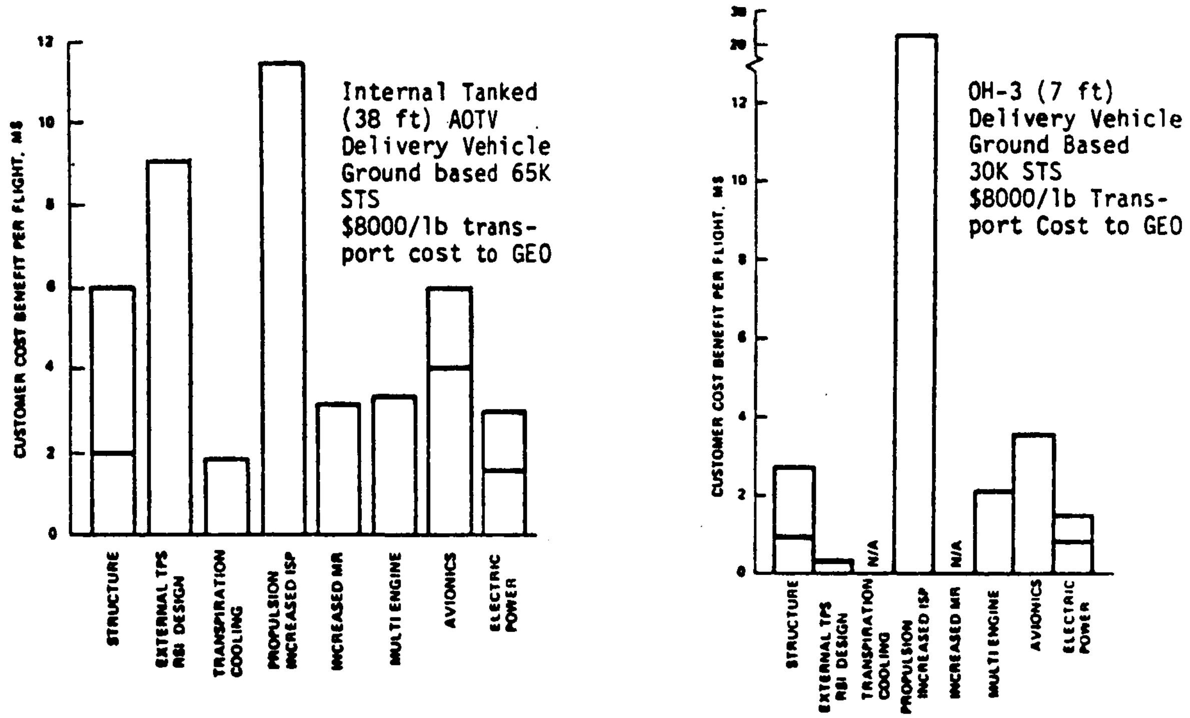
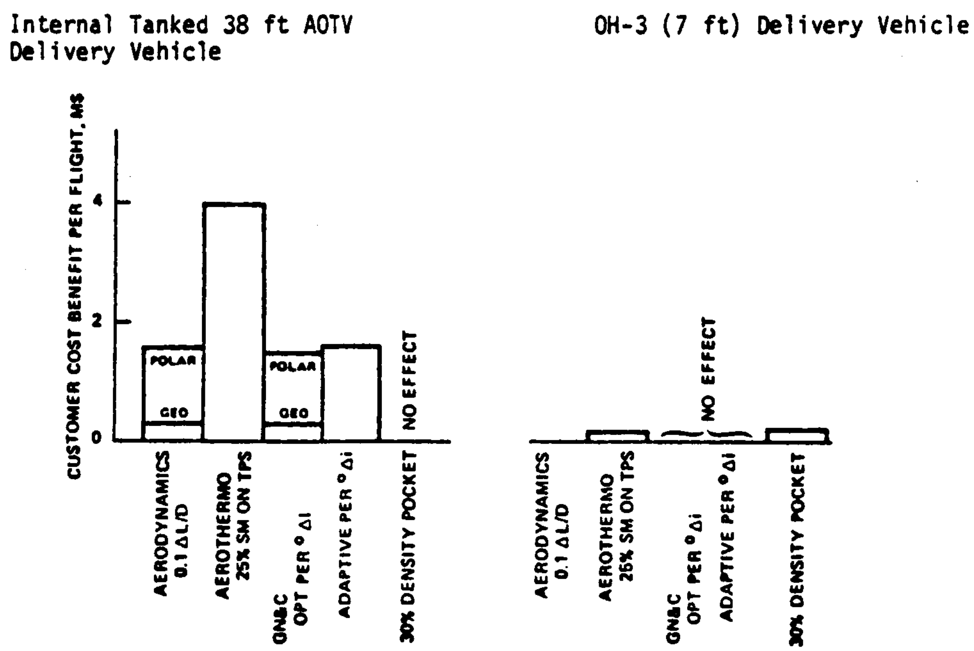


Figure 2.1-15 Effect of Technology Advances on Customer Cost Benefit



differences in the effect of incremental L/D on payload delivery capability, $\Delta W\ P/L / \Delta L/D$, between the GEO and 6 hr polar delivery missions.

2.1.4 Technology Payoffs

A detailed review of the current state-of-the-art in the various technology and subsystems areas was conducted to serve as a baseline point of departure for this study. Technology advancement possibilities identified in numerous recent studies of OTV, AOTV, SDV, and STS were reviewed. These results are compared with our in-house data base and parameters selected that represent improvements due to nominal expected growth resulting from normal funding of these technology areas. A number of these improvements resulting in from 10 to 70% reduction of subsystem weight are summarized in Figure 2.1-13. Other improvements include increase of maximum operating temperature of the thermal protection system elements, and others that will be identified in the discussion on subsystem trades.

Various techniques exist for ranking the technology benefits. The method selected for this study is as follows: given a subsystem weight reduction or other performance improvement possibility, the effect on increased payload weight was determined and this payload gain was converted to a customer cost benefit (i.e., money saved by the paying customer on Shuttle launch charges) assuming a nominal delivery cost to GEO of $8000 per lb. The mid L/D AOTV payload delivery sensitivities of Figure 2.1-12 have been combined with delivery cost and subsystem weight reduction possibilities to generate the results summarized in Figures 2.1-14 for the 38 ft and OH-3 delivery vehicles. Note that the 38 ft single stage vehicle has very different technology payoffs from the small OH-3 staged vehicle. However, both vehicles benefit substantially from high I_{sp} engines ($\sim$480 sec).

Additional technology advance benefits are summarized in Figure 2.1-15 for both vehicles. Aerodynamic uncertainties due to viscous and rarefaction effects will exist and could produce as much as ± 0.1 change in L/D. This uncertainty requires a propellant contingency which in turn decreases the payload delivery capability. Flight vehicles have typically flown initially with a safety margin in the thermal protection syste of as much as 25%. This translates into a very large payload loss (cost benefit loss) for the 38 ft delivery vehicle. A much smaller effect (almost negligible) is produced on the OH-3 vehicle due to its much smaller size. In the GN&C subsystem area, the ability to obtain aerodynamic plane change is translated into payload gain (from reduced propellants) and hence customer cost benefit. The value of an "optimum" guidance system that has been selected because it is capable of obtaining the most aerodynamic plane change from a given vehicle configuration is illustrated for one degree of incremental plane change. The value of an "adaptive" guidance system that has the capability of updating during the early portion of entry is illustrated for each additional one degree of plane change that can be generated. The effect of encountering a 30% density shear (pocket) similar to that experienced by a recent STS flight has been demonstrated to have no effect on a vehicle with L/D = 1.5 but to have a small effect on a vehicle with L/D = 0.6.

Some of the technology issues are more nebulous to quantify at this stage in the program but our best engineering judgment has been summarized in Figures 2.1-16 as to the relative importance of these issues.

Another way of evaluating the benefits of technology advances is to compare the effects of advances on the payload delivery magnitude. These results are summarized in Figure 2.1-17 where they have been ranked in order of decreasing importance for each of the vehicles.

A Technology Plan is presented in Volume II where the current state-of-the-art is identified and objectives and technical approach are enumerated.

2.1.5 Attractive Ground Based AOTV Configuration Approaches

Numerous single stage (internal tanked), stage and a half (one drop tank), and two stage AOTV designs have been explored. Two vehicle designs stand out as offering some real advantages. Figure 2.1-18 outlines a vehicle, "H1M", which is capable of bringing and returning a 2-man crew and their tools from low earth orbit (LEO) to geosynchronous orbit (GEO) during a 6 day mission. In addition, 2100 pounds of useful payload (like propellants, replacement components, etc.) are delivered and remain in GEO. The outstanding characteristic of this mission is that it is launched on a single shuttle flight (as a 65,000 pound payload). All prior studies have indicated the need for multiple shuttle launches to deliver a crew of 2 and some payload to GEO. With Shuttle launch costs approaching a $100M per flight by the end of this decade, single launch scenarios offer very substantial cost advantages.

Figure 2.1-18a shows AOTV "H1M" configured for orbital operations, Half of the aerodynamic shell covering the aft concial frustum has been rotated 180° to expose the interior of the vehicle to free space. This permits internal navigation and communication components to function without interference from the aeroshell. It also permits the crew capsule to rotate 90° out of the main body of the AOTV, providing the crew with free access to a worksite. The forward end of the vehicle contains a hinged aerodynamic nose (shown in open position) and a large Liquid Hydrogen (LH) tank. By designing this tank external to the aero-shell, a substantial amount of structural and thermal protection system weight is saved. Prior to major velocity changes (engine burns), the crew capsule is rotated within the AOTV (so the vertical centerline in Figure 2.1-18a is coincident with the vehicle centerline) and the aeroshell over the aft

Figure 2.1-16 Mid L/D AOTV Technology Issues

	Important	Minor Impact	Ground Test	Flight Test
Aerodynamics				
Atmospheric Rarefaction and Uncertainty Effects on AOTV Performance				
- Aero Plane Change Capability		X		
- Control Flap Effectiveness	X		X	X
- Dynamic Performance During Atmospheric Exit	X			X
Vehicle Aerodynamic Uncertainties	X		X	X
Aerothermodynamics				
Impacts Max TPS Surface Temperatures				
- Atmospheric Rarefaction Effects	X		X	X
- TPS Surface Finite Catalytic Effects	X			X
- Equilibrium Hot Gas Radiation		X		
- Non-Equilibrium Hot Gas Radiation	X			X
- Boundary Layer Transition of Large Axisymmetric Vehicles	X			X
- Flap/Body Shock Interacting Flow-fields	X		X	X
- Leeward Side Heat Transfer	X		X	X
TPS				
Increased Allowable Maximum Operating Surface Temperatures	X		X	
Increased Maximum Allowable Structure-Bond Line Temperatures	X		X	
Coating Weight Reduction/Elimination	X		X	
Thermal Conditioning Prior to Entry	X		X	
Transpiration Cooled Nose Enables One Pass Capture	X		X	X
GN&C				
Optimum Guidance	X		X	
Adaptive Guidance	X		X	
Atmospheric Density Uncertainties		X		
Vehicle Aerodynamic Uncertainties	X		X	

Figure 2.1-17 Summary of Payload Delivery Improvements Due to Technology Advances

Subsystem		38' Delivery	
		$\Delta W_{P/L}$	$\Delta W_{P/L}\%$
Structure	10-30%	253-759	1.8-5.3
TPS Design			
Cold Soak	23%	464	3.3
Coating Reduction	9%	181	1.3
600°F Soak Out	37%	746	5.3
Higher TPS Operating Temperatures			
Reduced Wt.	10%	202	1.4
300° = $\Delta \ell$ of 5.5°		187	1.3
Use Transpiration Cooled Nose for			
5 x GEO return		238	1.7
Avionics	50-70%	536-750	3.8-5.3
Electrical Power Supply	20-38%	208-395	1.5-2.8
Engine Performance	37 sec.	1443	10.2

frustum is closed. Before atmospheric entry, the LH tank is staged (an on-board rocket sends it on a burn-up trajectory), flaps are deployed and the nose is closed. "H1M" is now in the atmospheric entry configuration shown in Figure 2.1-18b. It is estimated that its real (non-Newtonian) [Lift/Drag]max ratio is 1.2. To perform its mission, it must have an (L/D) max of 1.04 to aerodynamically effect an orbital plane, change of 14.6°. The additional L/D provides a margin of safety which enables more confidence that mission goals can be met. The deployed flap shown at the aft end is schematic only. Although a split flap system is baselined for handling roll assymmetry, internal moving mass systems are also candidates. Most vehicle configurations have been established to maintain the center of pressure at the nominal vehicle center of mass (CM) without the use of a flap. Use of a flap for axial CM trimming may be required in some cases.

The "H1M" mission is enabled by two advanced technologies. Aerodynamic braking on return to LEO saves the propellant necessary to decelerate the AOTV by about 8000 ft/sec. This manned mission to GEO would be impossible (on one Shuttle launch) if that propellant had to be carried on the mission. The L/D of 1.04, which permits 14.6° of aerodynamic change of orbital plane, allows a 2100 pound payload to be delivered. If all plane changing (28.5°) had to be performed propulsively, the additional fuel would have eliminated the entire 2100 pound payload. Similarly, advanced propulsion technology also enables this mission. The specific impulse of current RL10 engines is 447 seconds. To deliver 2100 pounds of payload to GEO on the "H1M" mission, 479 seconds of Isp is required in addition to the L/D = 1.04. To perform the "H1M" mission with no payload to GEO, 459 seconds of specific impulse is required. More than high performance is necessary for "H1M" engines. For a given thrust level and nozzle expansion ratio, a large number of small engines provides a significantly smaller AOTV than would a single large engine. The smaller AOTV weighs less and has a better chance of fitting within a single 60-foot long orbiter cargo bay. Also, multiple engines can provide a level of redundancy that is highly desirable (fail safe) for manned missions.

Another valuable use of advanced technology is shown in Figure 2.1-19. A small, re-useable AOTV whose primary mission is to deliver payloads to a GEO transfer orbit near 28° inclination is shown in Figure 2.1-19a. Since the "OH-3" primary mission keeps it near its orbital inclination at launch, it doesn't need high L/D for plane changing maneuvers. The configuration shown has an L/D in the neighborhood of 0.4, enough to vary "OH-3"'s altitude and assure atmospheric capture on one pass despite large variations in expected density. The AOTV contains a small amount of internal propellant to perform a final circularization phasing burn (to rendezvous with the Orbiter) after exiting the atmosphere in a lofted trajectory. The propellant necessary to perform a satellite delivery is stored externally, in throw-away drop tanks. This staging arrangement allows "OH-3" (with a dry

Figure 2.1-18 Small Manned AOTV "H-1M"

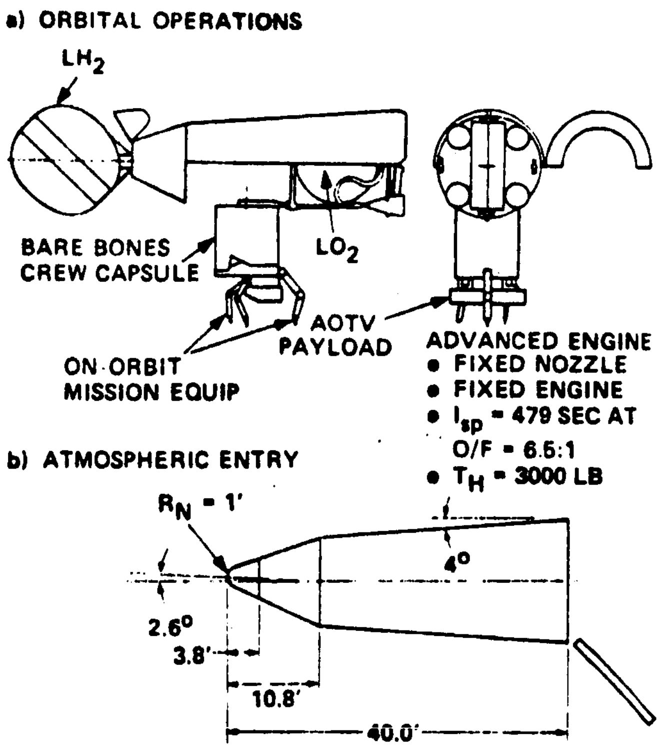
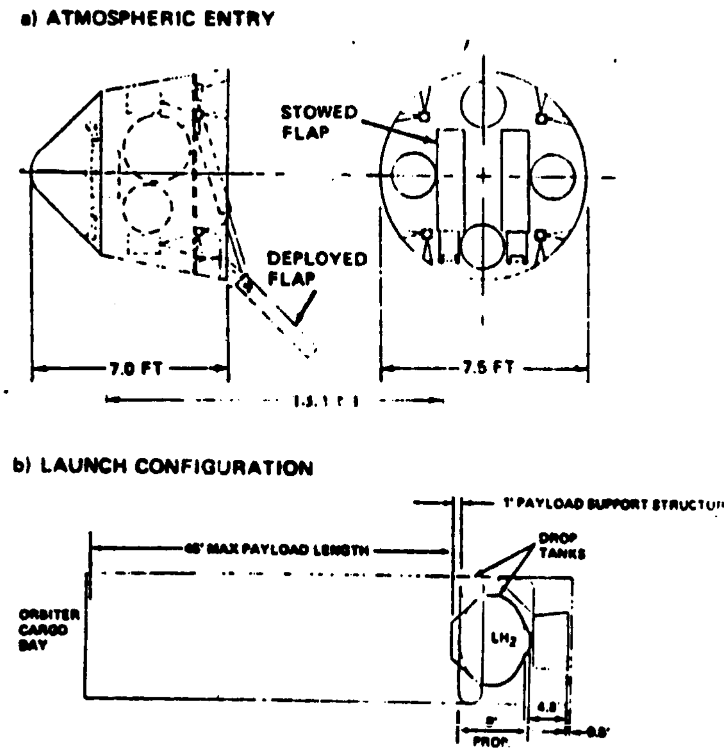


Figure 2.1-19 AOTV "OH-3"



weight of 4000 pounds) to weigh one half of the lightest AOTV designs published by this date. It is an extremely cost effective perigee kick stage. Earth to GEO transport costs average around $8000/lb using a 65K STS and OH-3.

The Figure 2.1-19b shows one way in which the short length of "OH-3" can be used to advantage. The tankage shown, in combination with four 3000 pound thrust, 476 second specific impulse engines, is adequate to deliver an 11,000 pound spacecraft (with its own propellant and propulsion system) to a GEO transfer orbit. The figure shows a single long payload. However, a single short (<14 feet) payload can be supported and one-half of the payload bay would remain empty. Since the entire launch stack weighs about 30,000 pounds (including ASE), one half of the cargo carrying capacity of a 65,000 pound lifting Shuttle can be used by another paying customer. Since Shuttle payload charges are based upon using 75% of capacity (for full launch cost), payload cost will be approximately $2M per foot of length. Consequently, a flight schedule of 10 per year promises a savings of $20M/year per foot of length saved in the next generation U.S. upper stage vehicle. "OH-3", or a variation on its theme, appears to be an excellent contender for this role.

2.1.6 Payload Delivery Costs

A Work Breakdown Structure (WBS) and related project costs have been developed for selected AOTV options. Phases covered include DDT&E, production, and operations. Program cost estimates include only those incurred by the prime contractor. Some of the major user launch cost considerations are enumerated on Figure 2.1-20. Operation costs and earth to LEO transport charges have been converted into payload delivery costs for GEO delivery. A summary of these cost results is presented in Figure 2.1-21 for the various AOTV's examined and in Figure 2.1-22 for the OH-3 type vehicle. The discontinuity in the curve denotes the transition from one set of drop tanks to two sets of drop tanks. Maximum cost efficiency occurs when the payload bay is loaded to capacity (60 ft and 65,000 lb). This condition produces a "cost to GEO" of about $6000/lb (off the curve for the OH-3 tank system that was outlined during Phase I). However, a fully loaded STS cargo bay is not considered to be typical of STS operations with cryo OTVs. A prior manufacturing study had indicated that 83% utilization of the cargo bay is representative. Applying this factor to a maximum GEO delivered weight of 16,000 lb produces a typical OH-3 GEO delivered weight of 13,300 lb (with two sets of drop tanks and two or three satellites) and a typical "cost to GEO" data of Figure 44 does not contain amortization of development and first unit costs for OH-3. IF DDT&E and the cost of one vehicle are amortized over 43 flights, the average cost of delivery to GEO increases by $1000/lb (at 13,300 lb). Consequently, we have used $8000/lb as a representative cost to deliver payloads to GEO using OH-3.

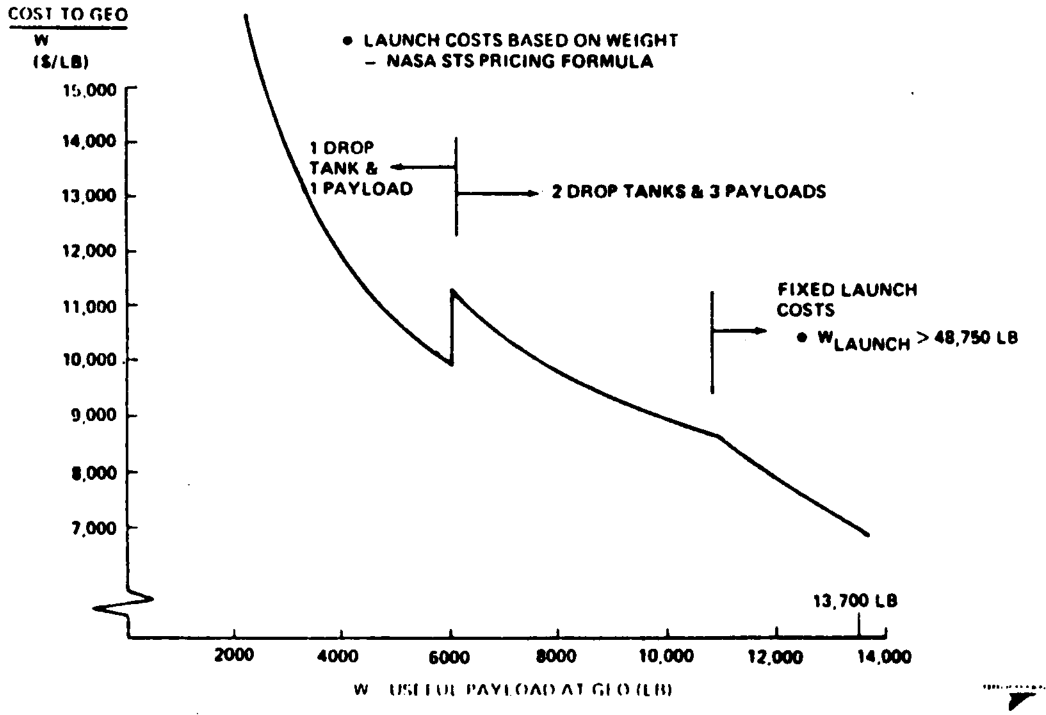
FIGURE 2.1-20 SOME USER LAUNCH COST CONSIDERATIONS

- THE MAJOR LAUNCH COST IS RENTING SHUTTLE PAYLOAD BAY
  - PAYLOAD + STAGE LENGTH >45' $\}$ \$80M +
  - PAYLOAD + STAGE WEIGHT >50,000 LB IN 1990
- SUBSTANTIAL EFFICIENCY IS AVAILABLE FROM ROCKET STAGING
  - VEHICLE SIZE AND PROPELLANT NEEDS GREATLY REDUCED
- COST OF PROPELLANT AND THROWAWAY STRUCTURE
  - AN ORDER OF MAGNITUDE LESS THAN STS LAUNCH
- COMMERCIAL USER WANTS GEO DELIVERY AT MINIMUM COST
  - REDUCE UPPER STAGE LENGTH TO MINIMUM
  - REDUCE UPPER STAGE WEIGHT TO MINIMUM
  - STAGE AT GEO ALTITUDE & $i \approx 26^{\circ}$
  - PAYLOAD CONTAINS ITS OWN APOGEE KICK STAGE
    - SMALL COST TO SATELLITES WHICH ARE AUTONOMOUS VEHICLES

FIGURE 2.1-21 BI-CONIC AOTV COST SUMMARY

- PRIME CONTRACTOR COSTS IN 1984 \$
- COSTS ARE FOR DESIGN, DEVELOPMENT, TEST AND ENGINEERING PLUS FIRST UNIT PLUS SPARES
- AOTV PROGRAM
  - OH-3 $\longrightarrow$ \$630M
  - OH-1 $\longrightarrow$ \$660M
  - INTERNAL TANKED GEO DELIVERY VEHICLE $\longrightarrow$ \$650M
  - H-1M (INCLUDING CREW MODULE) $\longrightarrow$ \$1380M
- USER COSTS FOR GROUND TO GEO DELIVERY WITH OH-3 AND STS
  - \$ DEPENDENT ON PAYLOAD SIZE, WEIGHT AND QUANTITY
  - EFFICIENT USE $\longrightarrow$ FROM \$6900/LB TO \$9300/LB FOR 9000 LB< Σ PAYLOAD WEIGHT<13,700 LB
  - INEFFICIENT USE $\longrightarrow$ UP TO \$14,000/LB FOR PAYLOADS AS LIGHT AS 3000 LB @ GEO

Figure 2.1-22 User Costs vs. Payload Weight: Ground Based OH-3



2.2 Summary

Substantial AOTV performance improvements can be obtained by developing enhancing technologies such as:

- Low thrust (2000 to 3000 lbs) advanced expander LOX-hydrogen engines with specific impulse of 480 to 490 sec,

- Reducing the external thermal protection system weight by reducing the coating weight and incresing the maximum allowable bond/structure temperature,

- Reducing the structural shell weight by improving the quality of the design allowable data, or use of advanced structural materials,

- Reducing the avionics subsystem weight by employing laser gyros, a data bus, advanced spacecraft flight computers, and perhaps decreasing the level of redundancy and autonomy.

It was determined that small vehicles, as used in two stage (perigee kick) delivery, have very different cost benefits than larger single stage vehicles and that within any staging class of ground based vehicles,performance sensitivities and technology cost benefits are independent of L/D.

Numerous system payoffs were also identified that included:

- Use of mid L/D AOTV provides significant aerodynamic plane change capability (20^{o} for return from GEO with L/D = 1.5) and control authority over trajectory dispersions and off-nominal atmospheres.

- A single STS flight manned mission to GEO with delivery of a one ton payload is possible with the 65 KSTS, mid L/D AOTV, an advanced cryofueled engine and lightweight ASE (3000 lbs).

- Delivery of very long payloads (45 ft) is possible by use of very short AOTV's with drop tank.

- Ground based AOTVs can reduce average Earth to GEO transport costs to $8000/lb for multiple satellite launches.

2.3 Recommendations for Future Study

Based on results of this study, and the increasing interest in a space station, it is recommended that the two major areas of 1) propulsion subsystem-AOTV configuration interaction issues and 2) technology benefits and payoffs of a space based

AOTV be further pursued at this time. The propulsion subsystem options offer alternative technical approaches to performing the attractive manned GEO mission (on one 65K STS launch) which is outlined in this study. These propulsion issues are outlined in Table 2.3-1. Numerous other high payoff technologies have been identified in Paragraph 2.1.4 and a plan for their pursuit included in Volume II.

TABLE 2.3-1 Engine Recommendations and Options for Man Rated Bi-conic AOTV

- At this time, six fixed, low thrust ($\sim$2000 to 3000 lb), advanced expander, LOX-hydrogen engines are strongly preferred
  - New engine ROM development costs are $\approx$ $300M
  - Is performance gain (man to GEO on one 65K STS flight) worth the expense?
- Some alternatives to new LOX-hydrogen engine development that seem worthy of future study:
  - Three RL 10A-3-3A engines on H-1M type vehicle incorporate "improved technology" subsystem weights
    - Explore effects of enhanced STS cargo capacity (65K, 75K, 100K) on this vehicle
  - Alternative LOX-hydrocarbon fuels (MMH, propane, methane, kerosene)
    - Explore AOTV system implications
    - Include effects of variable STS launch capacity
  - Storable propulsion (MMH, N2H4) AOTV in conjunction with heavy lift launch capability (100K STS or SDV)

3.0 REFERENCES

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